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A METHOD OF AEROPHOTOGRAPHIC MAPPING*

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This paper is not intended to be the description of a finished piece of work but rather is a report of progress in the development of a method of mapping which is only in a formative stage. It will not do therefore to expect that details will be given with the greatest accuracy and that all the problems connected with the work have been solved, although the general principles on which the method is based are fully established. We believe that the direction for progress has been pointed out but that many steps remain to be taken.

The work to be described is the outgrowth of experience in using the panoramic camera for topographic mapping in Alaska during the last eight years. The panoramic camera was first used in the Alaskan work of the Geological Survey by C. W. Wright in 1904, but it was not till after Wright had left the Survey and the work he began was taken over by Mr. J. W. Bagley, now Major Bagley, that the panoramic camera became one of the instruments regularly used for topographic mapping in Alaska.[1] The opportunity to take up and carry on this method was due primarily to Mr. A. H. Brooks, now Lieutenant Colonel Brooks, Chief of the Alaskan Division.

With the outbreak of the war in Europe and the rapid development of the airplane for military purposes the camera immediately took an important place as a means for gathering military information, including the making of maps. Major Bagley turned his attention to this broader field for the camera and asked the writer, who had had some small part in the previous work, to assist him. As progress was made it was found that more assistance was needed, particularly in photography, but also in many other ways, and Mr. J. B. Mertie was invited to contribute the benefit of his experience.

These investigations, which at first were carried on under the direction of the Council of National Defense and Mr. Brooks of the Alaskan Division of the Geological Survey, were later taken in charge by the Corps of Engineers of the Army and Lieutenant Colonel Marshall of the Topographic Branch of the Survey where they have remained to the present time. Money for the first experiments was furnished by the Council of National Defense, but the large sum needed for the construction of airplane cameras and transforming cameras was allotted by the Engineer Corps.

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*This paper (published with the permission of the Director of the United States Geological Survey) was read at the meeting of the Association of American Geographers at Baltimore in December, 1918. The writer takes this opportunity to express to Lieutenant Colonel Marshall, under whose immediate direction he has worked during the last year, his appreciation of the enthusiasm and generous encouragement given Major Bagley and himself.

[1] J. W. Bagley: The Use of the Panoramic Camera in Topographic Surveying, *U. S. Geol. Survey Bull. 657*, Washington, D. C., 1917.

PRINCIPLE AND PROBLEMS OF AIRPLANE MAPPING

The fundamental principle on which these investigations is based was first expressed, so far as the writer knows, by Theodor Scheimpflug, an Austrian army engineer, who gave many years of his life to the study of the problem. He, however, lived before the days of the airplane, so that his methods did not meet with the full success they deserved and he died without seeing any extensive application of them.

If a camera is carried above a horizontal plain and an exposure is made with the sensitive plate parallel to the plain, the resulting picture is a map whose scale is dependent on the focal length of the taking lens and the height of the camera above the plain. We apparently have at hand, then, a simpler way for making maps of many regions than the way ordinarily employed, for the airplane makes it possible to pass back and forth over a chosen area at will. Yet two difficulties are met when airplane photographs are employed in making maps. First, it is impracticable if not impossible with any means yet devised to keep the camera in a horizontal position; second, the angle of view of the fast lenses which must be employed in taking photographs from airplanes is small, so that the area covered at each exposure is also small and a great number of pictures must be taken in constructing the map. These, then, are the first problems that must be taken up if an accurate map is to be made at less expense than by the usual surveying methods.

The investigation to be described falls naturally into two divisions, of which the first deals with the airplane camera, that is with photographing the terrain. To this Major Bagley gave his attention. The second has to do with correcting the inclined airplane pictures; and for the study of the principles involved and the design of the transforming camera the writer is responsible. The questions relating to photographic methods and the construction of charts and computing devices for use with the transforming camera fell to Mr. Mertie.

The Airplane Camera

The difficulty of obtaining a lens which shall have speed and at the same time a wide angle of view is met by constructing a multiple camera with its three lenses and focal planes so arranged that the central plane shall be in a horizontal position and the other two shall be inclined at a fixed angle to it. The side pictures, because of their inclination, include areas outside the field of the central picture but overlap it slightly so as to give the means for joining them. A photograph of such a camera is shown in Figure 1.

The camera is about 25 inches high, 22 inches wide, and 7 inches thick from front to back. It consists of two parts, which may be separated from each other. The upper part is the magazine which carries the roll film. The lower part is really three distinct camera boxes, each fitted with its own lens and shutter, joined together.

The two side focal planes of the camera are inclined to the central plane at an angle of 35 degrees, and as a consequence the angle between the axes of the two side lenses and the central lens is the same. Lenses of about 7-inch focal length are used on the two side boxes and one of about 6 inches on the central box. The automatic shutters (Fig. 2) are released by a special cable release which acts on the triggers of the shutters through a synchronizing device shown in the photograph. This release is so adjusted that the shutters open and close at exactly the same instant. It is necessary that the time of exposure shall be as short as possible in order that a sharp image may be obtained. This necessity is the result of several causes, chief of which are the vibration of the engine and the angular movement or roll of the plane.

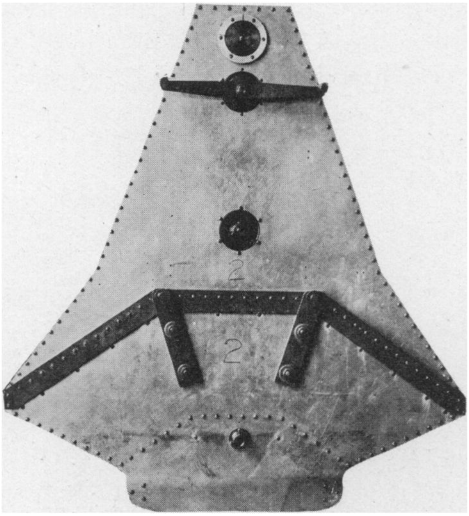

FIG. 1—Front view of the airplane camera showing the crank for winding the film and the index of the film measuring device.

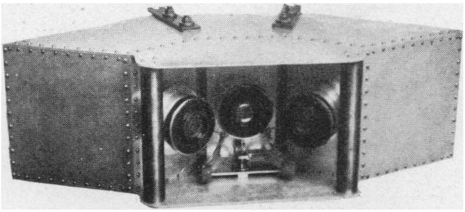

FIG. 2—The bottom of the airplane camera showing the lenses and the synchronizing advice.

When a film is to be inserted in the camera the magazine is lifted off the boxes, the unexposed spool is placed in position in its supports near the center of the magazine, and the free end is attached to the winding spool in the top of the magazine. After being replaced the magazine is made fast to the lower part by thumbscrews which bring the two sides closely together and prevent the entrance of light.

The film is wound off by hand by the crank seen in the illustration (Fig. 3). A registering device shows the length of film turned off when the crank is turned, and a marking device makes a mark on the film whenever the release is operated, so that the film may be cut without spoiling a negative. The film is 5 inches wide and has a maximum length of about 400 feet. The individual negatives are 5 inches wide and 6 inches long.

To mount the camera in the airplane a hole is cut in the bottom of the fuselage in front of the observer's seat, and a cradle, closed below by a sliding door for the protection of the lenses, is fastened securely to the floor. This cradle is padded with felt or sponge rubber, and the camera is strapped securely in it. Some airplane cameras are mounted on gimbal rings whose movement is damped by a dashpot arrangement. Such a mounting has been constructed for this camera but has not yet been tried out. It is not expected that this mounting will keep the camera in its proper position, for seemingly no device dependent on gravity alone for its effect has been able to do this fully. Probably it can do no more than reduce the errors of deviation.

MAKING THE EXPOSURES

The frequency with which exposures are made at a given altitude in getting pictures with proper overlap depends on the rate of movement of the plane over the ground, which in turn is dependent (1) on the airplane itself and (2) on the movement of the surrounding air; for the speed of the plane referred to the ground may be greatly increased or retarded as the plane flies with or against the wind. The time interval between exposures varies roughly from one-quarter minute to one minute. The observer making the exposures, however, does not rely on a time interval for getting properly spaced pictures but is chiefly dependent on a large negative lens about 6 inches square which is set in the bottom of the fuselage and enables him, as he views objects below him, to judge both the direction and the rate of movement over the terrain.

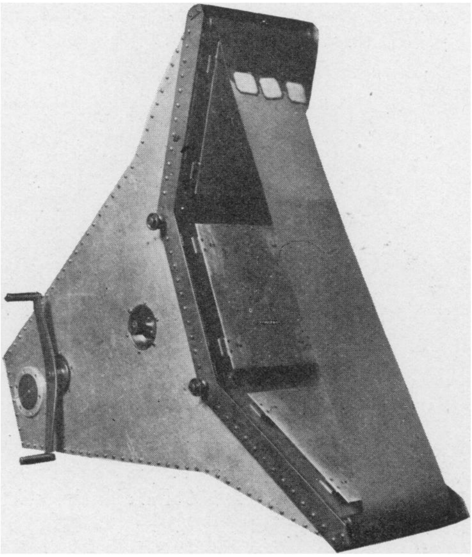

FIG. 3—The top of the airplane camera showing a film being inserted and the aluminum plates which indicate the position of the focal planes.

This camera still lacks one essential feature necessary to make it fill its purpose fully. It should have incorporated in it a device for recording on the film at the time of exposure the amount and the direction of the tilt of the central plate, for, as has been stated, it is not yet possible to keep the camera in a horizontal position. Correction of this fault appears to be only a matter of adapting to the camera some such principle as that of the gyroscope on which others have been at work and which seems now to be brought to a condition for practical application in this place.[2]

The Transforming Camera

Pictures taken with the airplane camera just described are subject to errors arising from the construction of the camera itself and from the tilt of the airplane, for it is only when the plate is taken in a horizontal position that the resulting picture is a map. These errors may be corrected graphically by projecting chosen points one by one on a plane representing the plane of the horizon, but the process is long and tedious. It was for the purpose of making these projections photographically that the transforming camera was designed.

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[2] Since this paper was written Lieutenant W. A. Hyde, of the Science and Research Division of the Air Service, and the writer have constructed a pendulous camera whose motions are damped by a gyroscope and have obtained encouraging results. This investigation is still in progress.

PRINCIPLES OF CONSTRUCTION

Before describing the working of the transforming camera it is desirable to state two principles on which the construction of the instrument is based.

Let $A\ P_1$ and $A\ P_2$ (Fig. 4) be two planes intersecting in the line A, and through any point O pass planes C_2O and C_1O parallel to planes $A\ P_1$ and $A\ P_2$ respectively. Project point a through point O onto the plane $A\ P_2$ in a'.

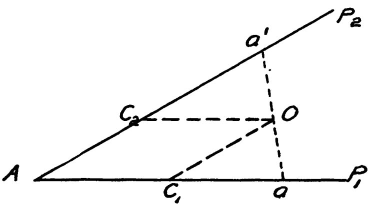

FIG. 4 (a)

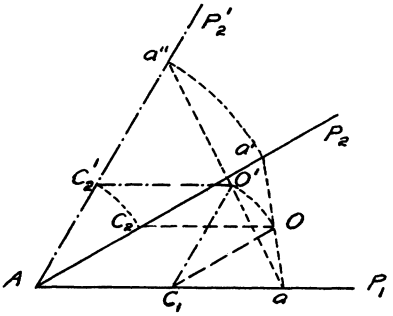

FIG 4 (b)

Now if we revolve the plane $A\ P_2$ about line A, the point a' is revolved to a'', the point C_2 to C'_2, and O to O'; and it may be demonstrated that the points a, O', and a'' lie in the same straight line, that is O' remains the center of projection for point a and its projection a'' on the revolved plane $A\ P'_2$.

This principle has an important use in the construction of the transforming camera. The second principle deals with lenses.

Let O (Fig. 5) be a lens of focal length f, whose axis is perpendicular to the plane passing through the optical center of the lens and the intersection of two planes $A\ P_1$ and $A\ P_2$. Further let O be so situated that it lies on the line which joins a, the intersection of $A\ P_1$ with a plane whose distance from O is twice the focal length, to b, the intersection of $A\ P_2$ with a plane whose distance from O is also equal to twice the focal distance.

These conditions may be expressed in a slightly different way, thus: Let the plane of the lens O pass through the intersection of the planes $A\ P_1$ and $A\ P_2$, and let O lie in the intersection of two planes C_1O and C_2O, which are parallel respectively to $A\ P_2$ and $A\ P_1$ and pass through the intersections of planes $A\ P_1$ and $A\ P_2$ with the focal planes of the camera.

If these two conditions are satisfied it may be proved that all points on either plane $A\ P_1$ or $A\ P_2$ are sharply in focus on the other plane.

This fact is the second principle which we need to use. Let us now see how these principles are applied to the correction of pictures taken in an inclined position.

Let P_2 (Fig. 6 a) be a negative on which are photographed the points A, B, and C. Let f be the focal length of the lens, i the angle of inclination of the plate, and D the height of the camera above the ground. The points a, b, and c are images of A, B, and C. Now the size of the image a, b, c, with any given inclination i, depends on the focal length of the lens and the height of the camera above the ground. This inclined photograph does not show a, b, and c in their true relative positions, but it can be made to do so by projecting the image onto some plane parallel to $A\ B$, such as P_1; and the scale of the resulting image depends on h, the distance of the plane P_1 from O. In order to show how this projection may be made photographically, produce the planes P_1 and P_2 till they intersect in A (Fig. 6 b), and draw C_2O and C_1O through O parallel to $A\ P_1$ and $A\ P_2$. Also replace the lens of the taking camera by another lens whose focal length is f_3, the length of the perpendicular let fall from either C_1 or C_2 to $A\ O$. It should be noted that $A\ O$ is the plane of the new lens. We have now fulfilled the conditions that must be fulfilled if we are to obtain sharp images of the points a, b, and c on the plane P; but we have limited ourselves to the use of one lens in making any given projection and shall require a different lens for every different angle of inclination. If, however, we revolve plane P_2 about the axis A we may vary the distance f_3 and thus, within certain limits, adapt our figure to whatever lens we find it convenient to use in the transforming camera. In the description so far the separation of the principal points of the lens has been disregarded. This was done to simplify the description and is entirely proper, for the same conclusions would have been reached had this been taken into consideration.

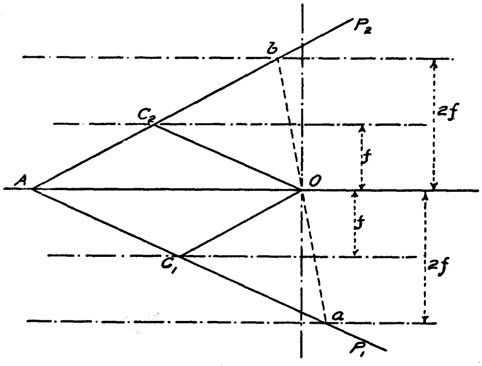

FIG. 5

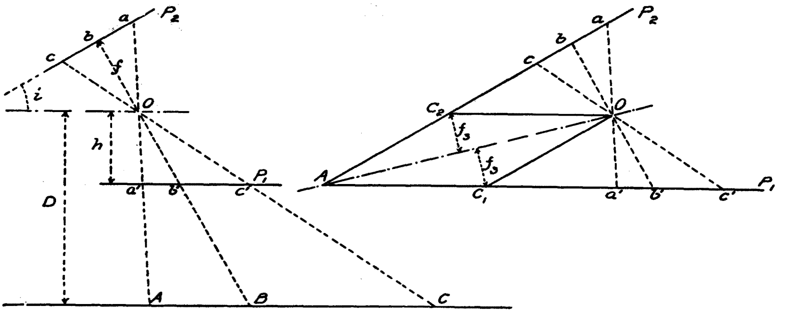

FIG. 6 (a) FIG. 6 (b)

FORM OF CAMERA

The simplest form of transforming camera capable of transforming photographs taken at different angles of inclination is one in which the two sides are hinged together and have their line of intersection in the plane of the lens. Such a camera is impracticable if the angle of inclination is small or has a wide range of values. The form of camera we have been using is shown in Figure 7. The two sides instead of being hinged together are made to revolve about vertical axes, and they together with the lens are capable of movements that permit all the conditions indicated in the previous diagram to be satisfied. The vertical axes may be moved to and from the lens, and in addition one axis and the lens may be moved transversely. The two axes are so connected with the frame supporting the lens that they and the lens are always in line. The large disks supporting the negative and the sensitive plate may be moved horizontally in their own planes.

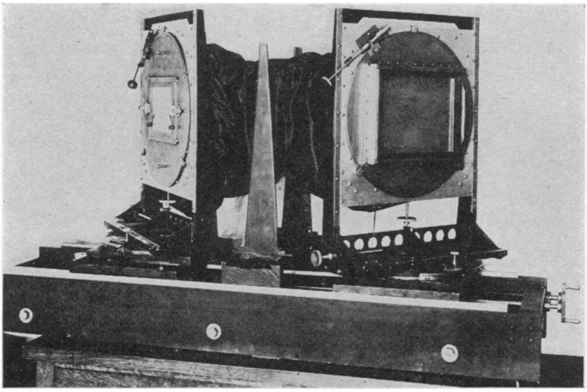

FIG. 7—The transforming camera. The sides are inclined toward each other showing the revolving disks on which the negative and the plate holder are carried.

The transforming camera is an instrument for doing accurate work. It is necessary that the films or plates be put exactly in their proper positions and that the settings of the scales be correct.

In setting up the transforming camera it is assumed that the focal lengths of all lenses employed, both in the airplane camera and in the transforming camera, are known and that the inclination of the picture to the horizon plane is known or can be found. With these data the setting of the instrument can be made after certain simple trigonometric calculations are completed, or the setting may be taken from charts constructed for the purpose. The charts are graphical representations of the trigonometric formulae and simplify greatly the work of making transformations. The camera is provided with scales and verniers so that the settings may be made with the required accuracy. It is not necessary to give here the formulae for obtaining the settings, but it should be said that it is nearly always best to have the solutions represented graphically.

TRANSFORMATION OF PHOTOGRAPHS

The inclined airplane photograph shows distant objects on a smaller scale than the near objects, so that the problem of the transformer is to restore a uniform scale to the picture by enlarging or reducing some part of it. Ordinarily one part of the photograph is enlarged, another is reduced, and the two parts are separated by a line where no change has taken place. Figure 8 shows one of the side pictures before and after its transformation.

The procedure followed so far in working up the airplane photographs is first to transform the side pictures to the plane of the central picture (Fig. 9), and when necessary all three to the horizontal plane, and then by an independent operation to bring all the pictures to the required scale, which, as a rule, is much smaller than the approximately 1:10,000 scale on which the original pictures were taken. After being brought to the chosen scale the pictures are cut to fit and joined together (Fig. 10). A certain amount of independent horizontal control is needed in this method of mapping as in all others, particularly if an extensive area is to be mapped, but our experience is not yet wide enough to show just how much of such control will be required. It will of course depend in part on the scale of the map.

DIFFICULTIES IN AEROPHOTOGRAPHIC MAPPING

The chief sources of difficulty that arise in making maps from airplane photographs lie (1) in the lack of suitable means for obtaining the data for transforming the inclined pictures into a truly horizontal position and (2) in the errors introduced into the pictures by relief of the terrain. The first of these has already been spoken of in describing the airplane camera and will be solved by installing in the camera the means for recording on the film at the time of exposure the direction and amount of inclination of the central negative. It may be solved in another way if sufficient horizontal control is available, for three or more points on the photograph may be brought into coincidence with corresponding known points plotted on the ground glass of the transforming camera, or rather on a tracing paper which can be compared directly with the image on the ground glass, and this of itself brings the picture into the horizontal position.

ERROR DUE TO RELIEF OF TERRAIN

The second source of difficulty, or that arising from relief of the terrain, becomes of greater and greater importance as the relief increases. If the scale of the map is large the error must be taken into consideration even when the relief is small. Apparently the errors of relief cannot be corrected directly by photographic means, and for the proper location of individual points it becomes necessary to determine the station point, or the point on the ground directly below the camera at the moment of exposure, and to find the position of the desired points by intersections from two photographs. This adds an extra operation to the work, which it is desirable to avoid where possible. Another line of attack on the errors brought in by relief is through the properties of stereoscopic vision. This

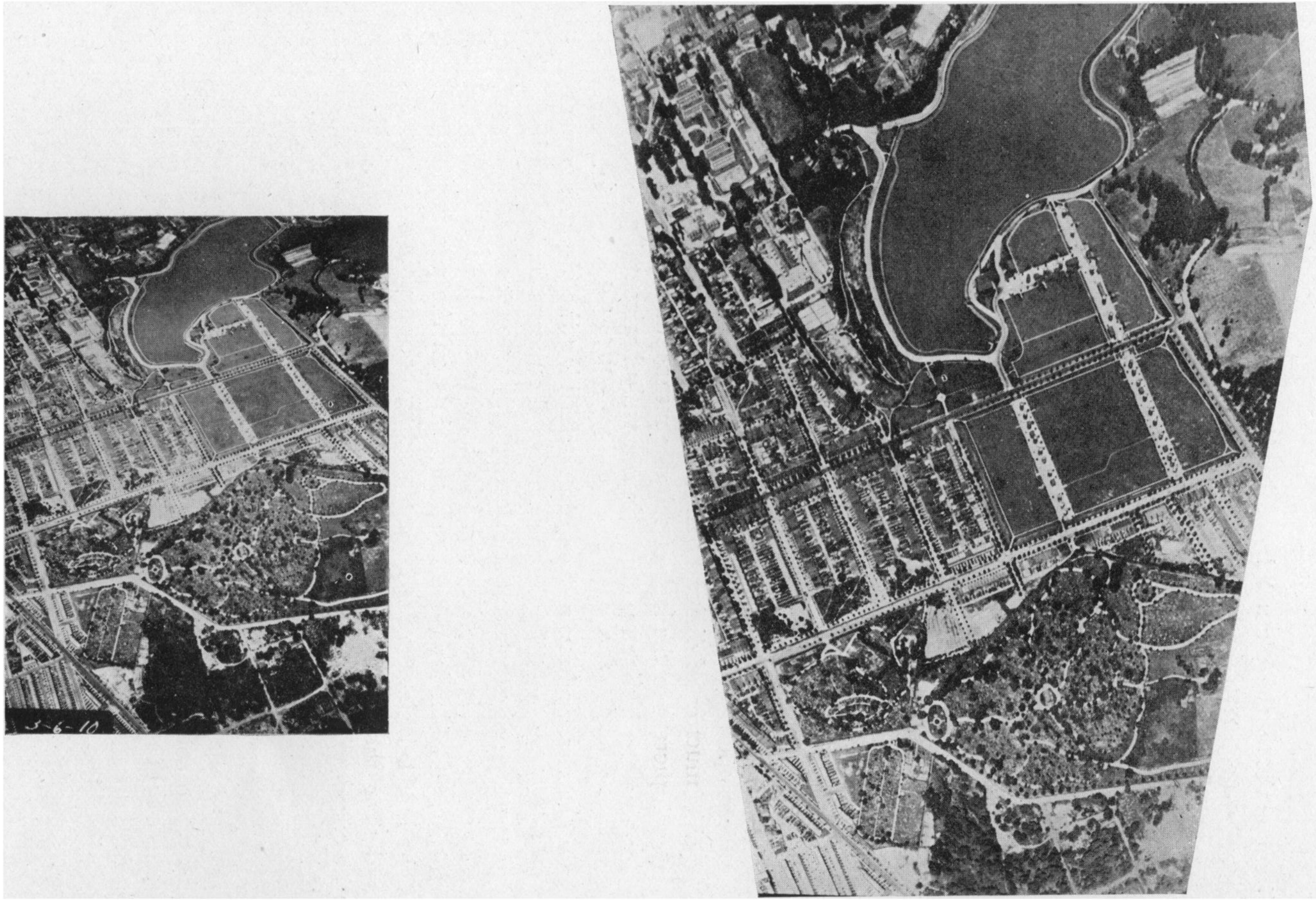

FIG. 8—On the left one of the side pictures taken with the airplane camera; on the right the same picture after it has been transformed to the plane of the horizon. About two-fifths the size of the original photographs.

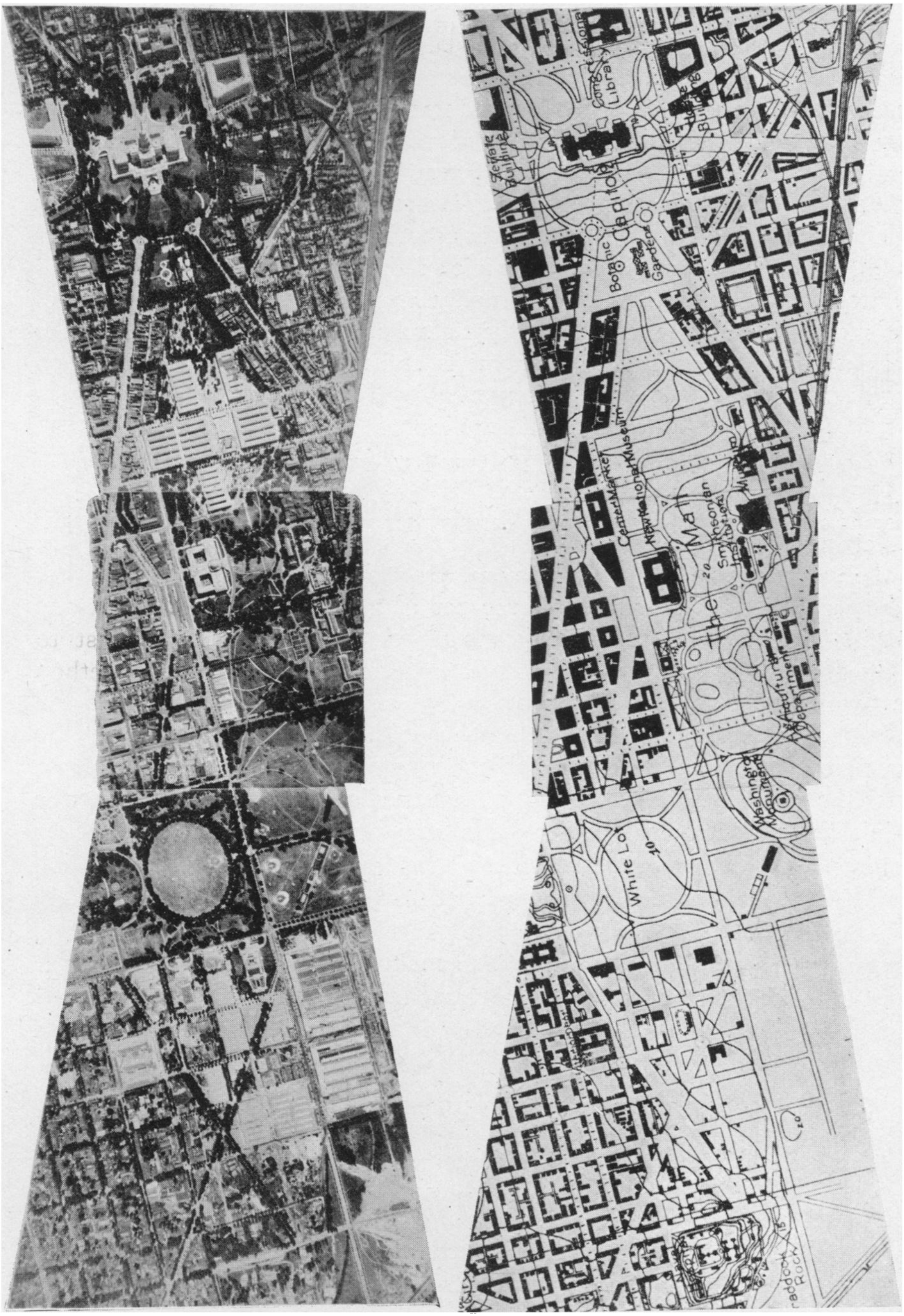

Fig. 9—A set of three pictures of a part of Washington compared with the map of the same section.

involves the use of overlapping pictures and some instrument such as the stereocomparator, constructed for accurately measuring parallax, which may be employed in correcting errors of relief and, if the necessary data are obtained, affords a refined method of drawing the contours to express the relief. This important part of the work is a feature on which we have hardly touched as yet. Fortunately a certain amount of error due to relief comes within the error allowable for the scale of the maps usually made in this country. "Mosaic" is a term commonly employed to designate most of the maps made from airplane photographs. It will be of interest to make a comparison between such maps and maps made by the method just decribed.

Advantages of Multiple and Transforming Cameras

The advantages of the method under consideration may be divided into two classes, those arising from the use of the multiple camera and those due to the use of the transforming camera. It will be well to state again that there would be no advantage in the use of a multiple camera if it were possible to get well corrected fast lenses of wide angle. The chief advantage of the multiple camera over the single-lens camera is the increased field of view which makes it possible to cover a given area with fewer flights and therefore in shorter time and at less expense. The area covered by the three pictures of the three-lens camera at a given elevation is about four times the area covered by the central picture alone, and this is roughly the ratio that holds between the three-lens camera and most of the single-lens cameras. Further the three-lens camera reduces the probability of leaving parts of the terrain unphotographed and makes easier the final assembly of the pictures. A uniform overlap in the series of pictures made during successive parallel flights is difficult to maintain, so that frequently it is found either that the overlap is too great or that a part of the terrain is unphotographed. A wide field of view in the airplane camera helps to minimize this difficulty.

The advantage due to the use of the transforming camera is chiefly that it makes possible the use of pictures that without it would be unusable or greatly in error because the subject photographed was not parallel to the plate and therefore the pictures do not have a uniform scale; but no advantages arising from it are such that they may not be enjoyed in either method. It would be much more nearly correct to say that until the means is devised for keeping the camera plate in a horizontal position the transforming camera is essential to either method if accurate work is to be done. So far as the writer's knowledge goes no airplane camera has yet been constructed whose pictures are not subject in some degree to errors arising from the tilt of the plane. In practically all this, error may be and often is much greater than any allowable error.

THE POSSIBILITIES OF AEROPHOTOGRAPHIC MAPPING

The advantages that will arise from the use of photographs taken from the airplane or dirigible airship for the making of maps can hardly be overestimated. These advantages are of many kinds and include among others greatly increased speed, greater accuracy in details, reduction in cost, and, for special purposes such as the use of aircraft pilots, the possibility of representing on the map the actual appearance of the terrain as it is seen from above. Further it will make possible the mapping of areas which for the lack of roads and other means of transportation or for other reasons are now practically inaccessible. When a strip of country from three to five or more miles wide can be photographed at the rate of seventy-five or one hundred linear miles per hour, according to the speed of the airplane, it is not difficult to see that the length of time per square mile devoted to actual field work in the older, established methods now in use must be even hundreds of times greater than in the new method.

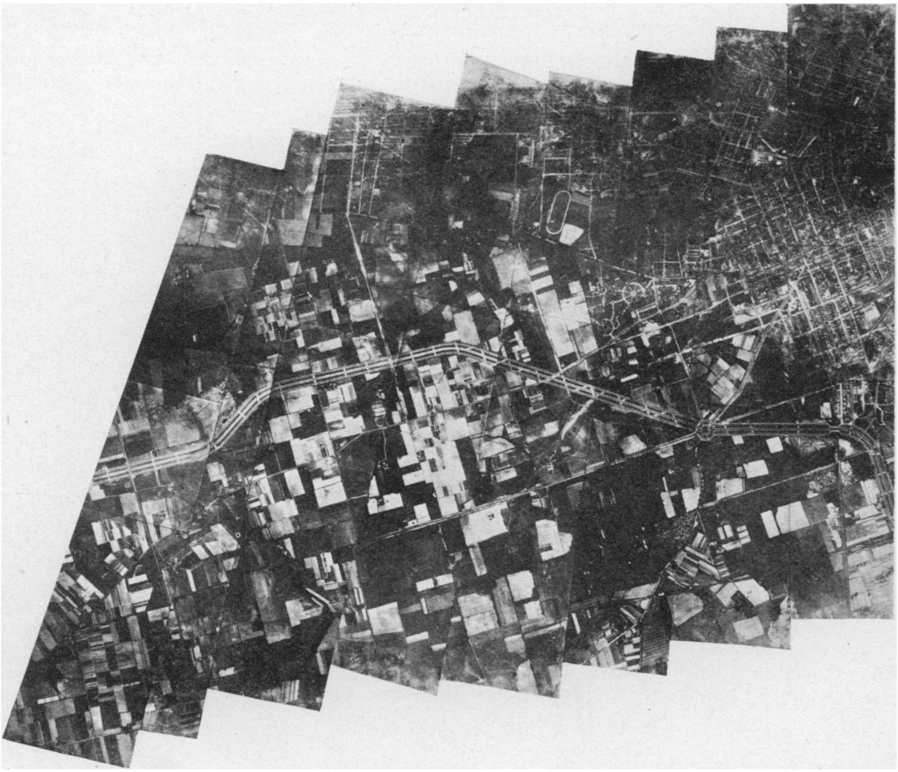

FIG. 10—A series of photographs taken with the airplane camera after they have been reduced to the horizontal plane and joined together.

The errors that arise from the relief of the terrain have been referred to and are fully appreciated, and for that reason it is believed that the first application of the method should be in areas of low relief. Many thousands of square miles of such land are still unmapped in the United States, including most of the Atlantic and Gulf Coastal Plain as well as great areas in the west. The Coastal Plain in particular is well adapted to test the merits of the photographic method of mapping, for it is a region of low relief, largely unmapped, and in many parts extremely difficult of access.[3] Another field of application in which it is believed that the photographic method will be most useful is in the revision of existing maps, as in the addition of features like new roads built since the map was made or of timbered areas not mapped originally. Only those who have had experience in the study of airplane photographs can realize fully the wealth of material they contain for the map maker.

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[3] Compare the preceding article by W. T. Lee: Airplanes and Geography, pp. 310-325.